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# Spectroscopy of a heated Yb-doped optical fiber with high aluminum content

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## ABSTRACT

The generation and amplification at wavelengths longer than 1100 nm is not straightforward when using Yb-doped optical fibers, since light emission of ytterbium occurs preferentially in the region of 1020 nm - 1100 nm with a maximum at 1030 nm. One well known approach is to heat the Yb-doped fiber up to temperatures above 100 °C. This increases the re-absorption in the lower emission band and also enhances at the same time the emission at longer wavelengths. Consequently, heating allows to extend the spectral gain-region of Yb-doped fibers by at least 60 nm up to 1160 nm. However, the drawback of this method is that it results in a shorter durability of the fiber, since heating damages the polymer-coating. Moreover, such a laser has a reduced overall efficiency, due to heating, isolation and heat removal issues.

It has been reported, that at the presence of an aluminosilica host (silica doped with Al) efficient laser activity at around 1150 nm can be achieved by heating the Yb-doped fiber to only 60 °C. In this work we investigate the spectroscopy of a heated Yb-doped fiber with a high aluminum concentration. The fiber is drawn in our in-house fiber drawing tower. The preforms are produced by the sol-gel-based granulated silica method which allows us to vary the aluminum as well as the ytterbium concentrations within a large range. The fiber is investigated with respect to their spectroscopic data as well as their lasing performance.

**Keywords:** Aluminum concentration in Yb-doped fiber, Extension of spectral gain-region of Yb-doped fibers, Heating Yb-doped fiber

## 1. INTRODUCTION

The generation of laser light sources in the yellow spectral range (560 - 580 nm) is due to the lack of efficient laser gain medias not straight forward. One approach is to build an infrared laser cavity at the wavelength of 1120 - 1160 nm, followed by a Second Harmonic Generation (SHG) crystal to frequency double the light. One possible design of such a setup is a linear, Fiber Bragg grating (FBG) based laser cavity with an Yb-doped fiber as gain medium. The benefit of such a design is not only a narrow banded laser line at a desired wavelength, which allows efficient SHG, but also the commercial availability of the fiber. In a previous work we demonstrated successfully such an infrared fiber laser with an output power at Watt-level; generated by a laser cavity design as described.<sup>1</sup> Currently, the limit of such a setup is the upcoming, parasitic Amplified Spontaneous Emission (ASE) at the wavelength of the ytterbium gain maximum at 1030 - 1060 nm. One possibility to generate more efficient laser light at long wavelengths is to heat up the Yb-doped fiber, since this causes a shift in the absorption as well as in the emission spectrum.<sup>2</sup> Heating a fiber, however, has several drawbacks. The polymer-coating takes damage, which results into a shorter durability of the fiber. Furthermore, the heat source demands for an extra effort in isolation and heat management and hence limits the design of the setup. This fact must be taken into account once a compact prototype of a lab setup is demanded.

It has been reported, that at the presence of an aluminosilica host efficient laser activity at around 1150 nm can be achieved by heating the Yb/Al-doped fiber to only 60 °C.<sup>3</sup> In this contribution we investigate the spectroscopy of a heated Yb-doped fiber with a high aluminum concentration, which is drawn in our in-house fiber drawing tower. The fiber was drawn by our production method, the sol-gel based granulated silica method, which allows an easy adjustment of the doping components concentrations.<sup>4,5</sup> The produced fiber is investigated with respect to their spectroscopic data as well as their laser performance.

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## 2. FIBER FABRICATION

Our sol-gel based granulated silica approach of fiber fabrication is summarized in Figure 1.<sup>5</sup> It combines the sol-gel based production of homogeneously doped silica granulate with the powder-in-tube technique, which allows an easy adjustment of the dopant concentration up to several at. %. The process starts from precursors mixed into a liquid solution resulting in a sol. Hydrolysis, condensation, gelatinization and drying result in a powder, where every grain is doped. Next, the powder is sintered and milled to a desired grain size of several 100  $\mu\text{m}$ . In order to reduce the scattering losses an intermediate vitrification step is added before the final fiber drawing. For this fiber, the vitrification process was done by drawing a droplet in the drawing furnace from the sintered granulate derived from the sol-gel process. We then took the upper part of this droplet as a core area for the powder-in-tube preform where the interspace was filled with pure silica granulate. The drawback of this method is the non-constant core diameter. In the latest development of the fabrication process, the vitrification is done by a  $\text{CO}_2$  laser treatment, which allows a constant core diameter. The final result is a step-index fiber with a homogeneously doped core and pure silica cladding.<sup>5</sup> The core precursor composition for our fiber is listed in Table 1. Phosphor is added as a co-dopant in order to increase solubility of the rare earth dopant as well as to suppress photodarkening.<sup>5</sup>

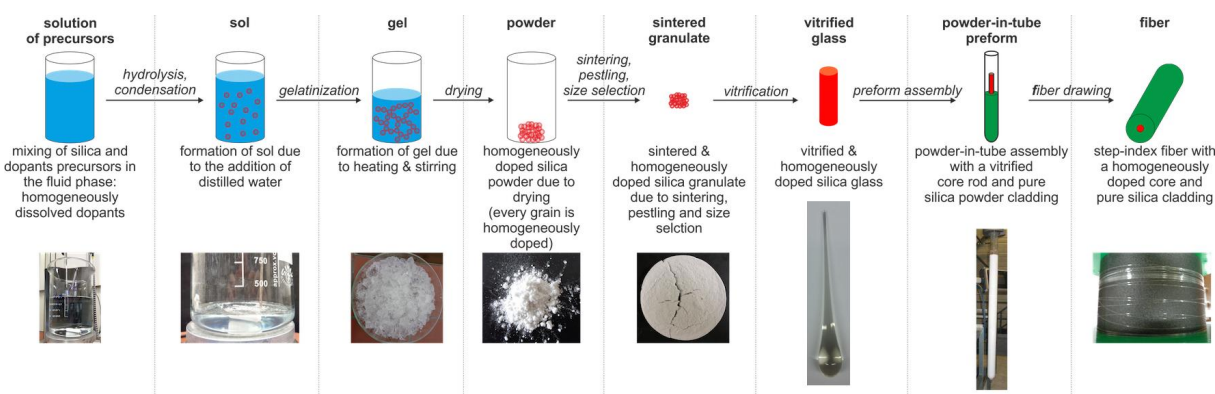


Figure 1: Schematic overview of our fiber fabrication process, the sol-gel based granulated silica method.<sup>5</sup>

Table 1: Core precursor composition

Precursor name	Chemical formula	At. %
Ytterbium(III) nitrate pentahydrate	$\text{Yb}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$	0.4
Phosphorus pentoxide	$\text{P}_2\text{O}_5$	2.4
Aluminum nitrate nonahydrate	$\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$	4

### 3. SETUP

Our setup to characterize the spectroscopic and laser characteristics is sketched in Figure 2. If the dichroic mirror M2 is mounted into the setup, port P2 allows to measure the residual pump. Without mirror M2, the setup changes into a single pass setup, which allows to measure the transmission of the signal as well as the residual pump.

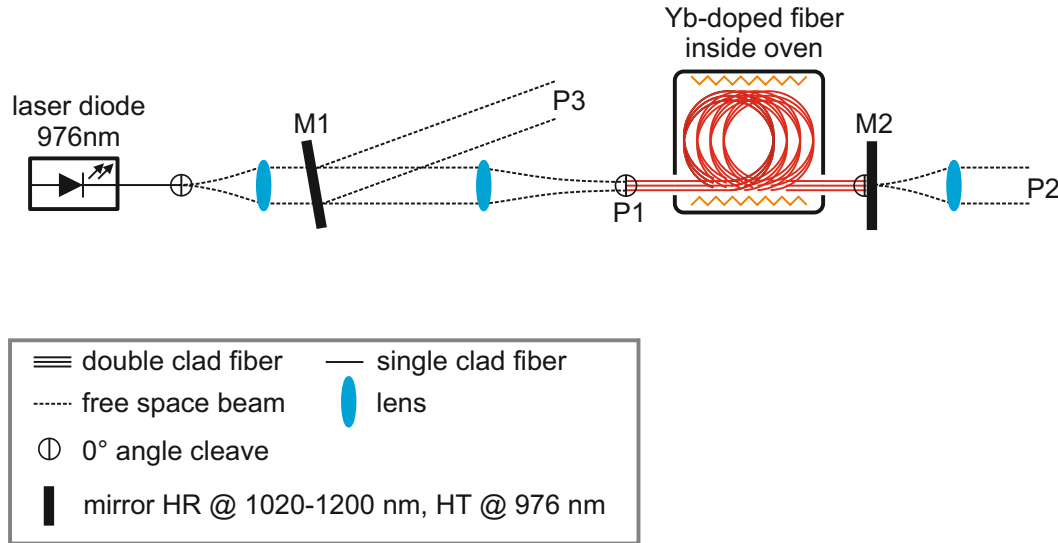


Figure 2: Schematic setup to characterize our fiber. Every end facet of a fiber is cleaved at an angle of 0°. P1 corresponds to the entrance facet of the Yb-doped fiber, where the pump light is coupled into the fiber. This cleave acts as a 4 % reflection mirror of the double pass setup. P2 is after the end facet of the Yb-doped fiber and after the dichroic mirror M2. At this position, the residual pump can be measured. The signal from the double pass can be measured at P3, since it is coupled out from the system with the dichroic mirror M1. Both dichroic mirrors M1 and M2 are high reflective for light at a wavelength of 1020 - 1200 nm and high transmitting for the pump light.

### 4. RESULTS

#### 4.1 Refractive index profile measurement

The refractive index was measured with an improved system, which is based on the refracted near field technique.<sup>6</sup> The new setup allows a fast capture of the 2-D refractive index profile of our fiber.<sup>6</sup> The measured values are given in Table 2 and depicted in Figure 3.

Table 2: Results from the refractive index profile measurement

	Value	Error
Index step	$5.1317 \times 10^{-3}$	$9.6453 \times 10^{-5}$
NA core	$1.1612 \times 10^{-1}$	$1.0933 \times 10^{-3}$

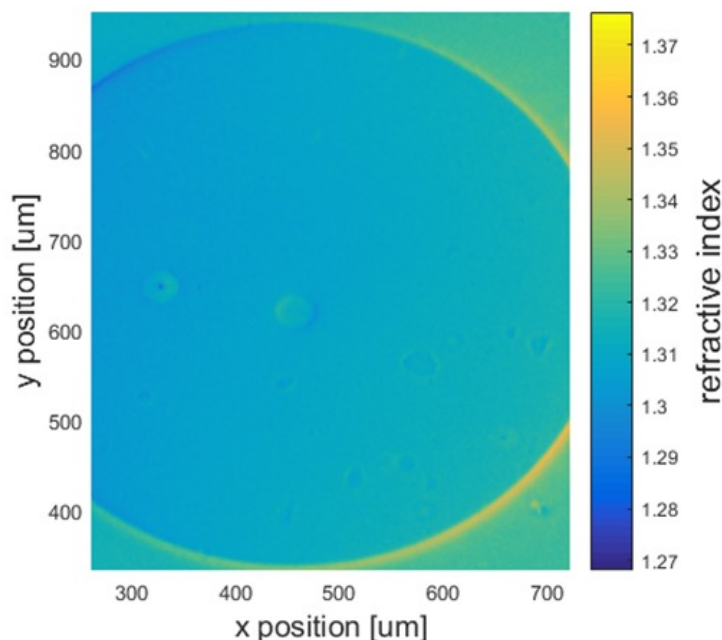


Figure 3: 2-D refractive index profile. The average core index is 1.3163 (err:  $9.5087 \times 10^{-6}$ ), the average cladding index is 1.3112 (err:  $1.6174 \times 10^{-5}$ ).

## 4.2 Lifetime measurement

The lifetime measurements of the upper laser level of the Yb was taken for our fiber as well as for a commercial one. The values are presented in Table 3.

Table 3: Results from the lifetime measurement

	Lifetime [ms]
Our fiber	$0.74 \pm 0.007$
Commercial fiber	$0.8 \pm 0.004$

## 4.3 Spectral measurements

The fiber was coiled on a cylindrical aluminum block, which is used as a heating source. To measure the forward ASE, the mirror M2 was removed from the setup. The Yb-doped fiber was then pump to a level below the laser threshold and heated to different temperatures. Figure 4 show the ASE spectrum for three different temperatures. A shift of the peak maximum by  $0.013 \text{ nm}/^\circ\text{C}$  is observed as well as a general increase of the emitted spectrum. At the peak maximum at approx. 1030 nm, the increase of the spectral emission is  $0.008 \text{ dB}/^\circ\text{C}$ , whereas at a wavelength of 1160 nm, the increase is  $0.014 \text{ dB}/^\circ\text{C}$ . While the increase at longer wavelength is similar to the values we observed for a commercial fiber, the spectrum shows a different behavior at the peak maximum at 1030 nm. In a previous work we observed a decrease of the spectral emission at 1030 nm.<sup>1</sup>

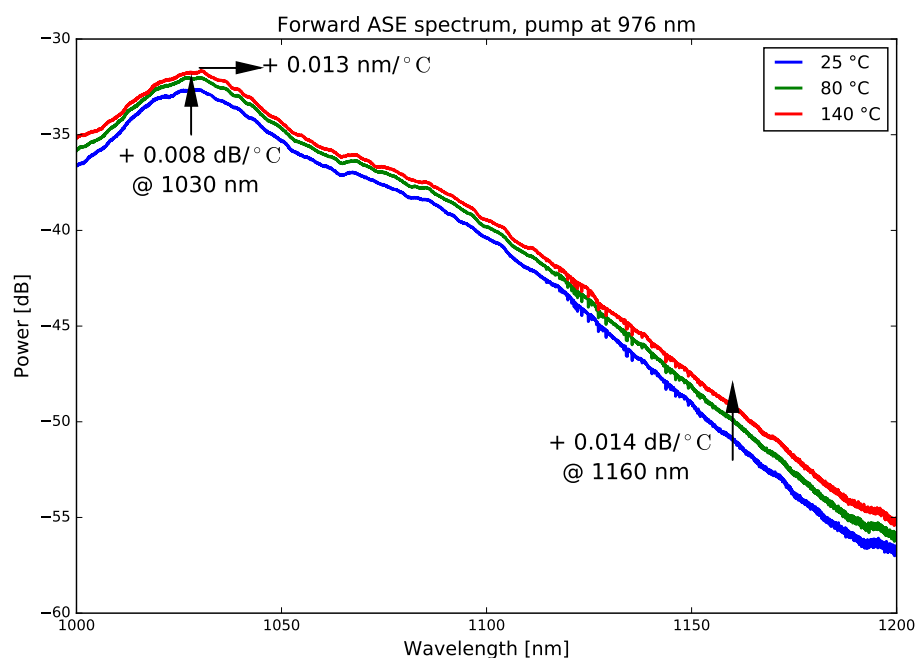


Figure 4: Forward ASE. The fiber was pump below the laser threshold and heated to different temperatures. An general increase of the spectral emission was observed for higher temperatures.

#### 4.4 Laser measurements

The fiber was investigated in two different setups, one is a single pass setup, pumped at a wavelength of 940 nm, the second one is a double pass setup, pumped at a wavelength of 976 nm. The laser characteristics are summarized in Table 4. Figure 5 indicate the slope efficiency for different temperatures of the Yb-doped fiber. The slope efficiency increases with increasing temperature of the fiber from 4.3 % at room temperature to 6.5 % at 140 °C. The power was measured with a thermophile power meter. Figure 6 shows the emission of laser lines, when the system is pumped with an absorbed pump power of 8 Watt. All laser lines are shifted to longer wavelengths, as the temperature of the fiber was increased.

Table 4: Laser characteristics.

	Double pass	Single pass
Pump wavelength [nm]	976	940
Fiber length [m]	5	2
Slope efficiency [%]	4-6	0.5
Laser threshold [W]	3.5	6
Temperature [°C]	25	25

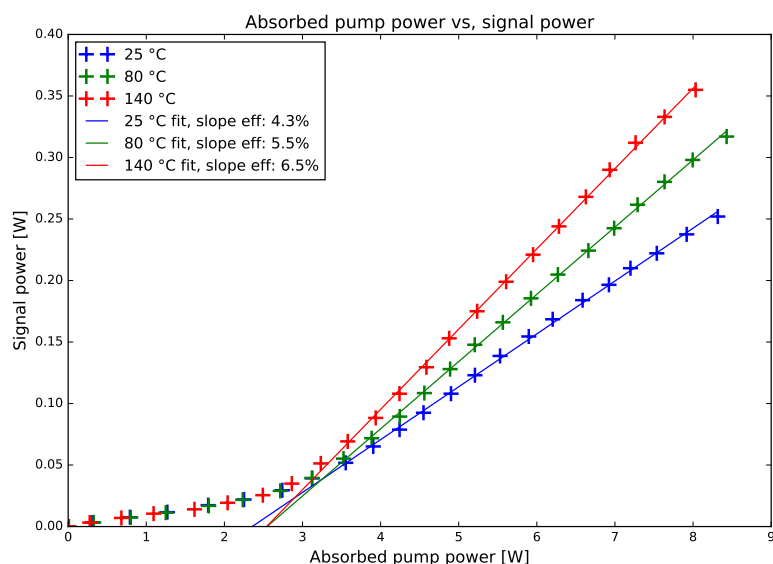


Figure 5: Absorbed pump power vs. signal power for a fiber length of 5 m, pumped at a wavelength of 976 nm. The slope efficiency increases with higher temperatures of the fiber.

## 5. DISCUSSION

The core size is, due to the fact that the core was vitrified by drawing a drop, not constant. Since this fiber is a very first prototype, we did not concern about this fact.

The two characteristics numerical aperture (NA core: 0.11612) and the lifetime ( $0.74 \pm 0.007$  ms) of our fiber show similar values to commercial fibers (NA core: 0.12, lifetime: 0.8 ms), both values deviate less than 10 %.

The shift of the spectral emission of a heated Yb-doped fiber is a well known fact.<sup>2</sup> While we observe a similar ( $+0.015$  dB/°C) increase of spectral emission at a wavelength of 1160 nm to our previous work, the spectral emission at the peak at 1030 nm behaves differently. In our previous work, we observed a significant decrease of the emission peak (up to  $-0.1$  dB/°C), while our fiber indicates an increase of  $0.008$  dB/°C. This leads to the assumption, that the absorption spectrum of our fiber differs from the commercial one.

Our fiber absorbs approximately 60 % of the coupled pump power, however, only a small percentage is converted into laser light. Since the fiber was heated by a heating source, which has a temperature monitor, we could also observe that the fiber heats itself up by pumping as well as the heating. Calculations confirmed, that the power required to heat up the heating source to the measured temperature corresponds to the power coupled into the fiber, but not converted into laser light. One explanation for this effect could be the presence of Yb-clustering. Yb-clustering would also result in a shorter lifetime, which corresponds to the fact that the measured lifetime of our fiber is shorter compared to the commercial one. Furthermore, the composition of Yb/Al/P is in progress to be optimized. Our assumption is that all of these drawbacks are responsible for the poor laser performance.

## 6. CONCLUSION AND OUTLOOK

We drew a Yb-doped double clad fiber with a high aluminum concentration. The laser performance with a slope efficiency of only 4 - 6 % is low compared to commercial fibers, and a self heating of the fiber was observed. However, since this is a very early stage of our research, further experiments need to be performed.

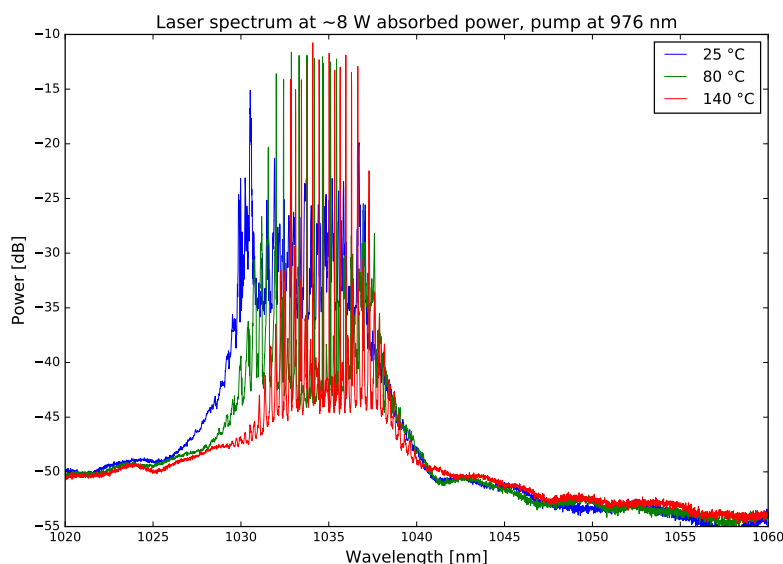


Figure 6: Laser emission for a fiber length of 5 m, pumped at a wavelength of 976 nm. The spectrum shows a competition of various laser lines and a general shift to longer wavelength for higher temperatures of the Yb-doped fiber.

## ACKNOWLEDGMENTS

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